Satellite Vibration on Image Quality Degradation of Remote Sensing Camera

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Abstract

Vibration is one of the important factors affecting the image quality of remote sensing camera for disturbing pixel-matched storage and causing image motion. Analyzing the influence of satellite vibration on the image quality degradation of remote sensing camera will be of great importance in compensating image motion and putting forward the satellite controlling index. Modulation transfer function (MTF) is a major index to evaluate the image quality of optical image system. This paper extends the vibration model from one-dimensional space to two-dimensional space based on the statistical moment theory and the theory in calculating MTF using Line Spread Function (LSF).

Key Word

Vibration; MTF; Two-dimensional space; Statistical moment

Introduction

Optical system and the vibration may cause a decline in imaging quality of space camera, when satellite remote sensing imaging. Although damping measures have been taken on satellite, these effects are still not completely eliminated. Therefore, the analysis of mechanical vibration is important in designing the optical mechanical structure and meeting the requirements of imaging system. MTF is modulus of the optical transfer function (OTF), which is a function describing the energy transfer of object imaging. So, MTF can evaluates the imaging ability of optical system objectively.

Kopeika et al. adopted the methods based on airspace or frequency domain for solving dynamic transfer function and taken experiments to test and verify. Wulich et al. adopted the method of identification of probability. However, those methods mainly studied the influence of one-dimensional vibration on imaging quality degradation of optical imaging system. The vibration, on the one hand, from the work environment of satellite, on the other hand from the optical system, and the form of vibration is not only limited along the optical axis or vertical to optical axis. So the analysis is not perfect just from the view of one-dimensional. In this paper, the method based on LSF to solve the transfer function is used to analyze the influence of vibration on imaging quality degradation of optical imaging system, and add the ideal of statistical moment extended to two-dimensional.

The MTF of the One-dimensional Space

Base on the knife-edge, the MTF is equal to the Fourier transform of LSF:

$$MTF(\omega) = F\left[LSF(x)\right] = \int_{-\infty}^{\infty} LSF(x)\exp(-j\omega_x x)dx \tag{1}$$

where set $x(t)$ is the relative motion of objects and the sensor in one exposure time, the LSF is the histogram of $x(t)$, as probability density function (PDF) of the movement. This method can also be used to analyze the MTF of random vibration.

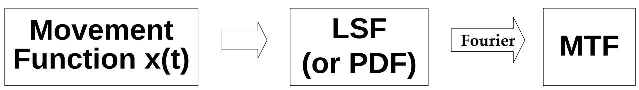


FIG.1. USING LSF TO CALCULATE MTF

Calculate MTF using Taylor expansion:

$$MTF(\omega) = \sum_{n=0}^{\infty} \frac{1}{n!} \left| \frac{\partial^n MTF(\omega)}{\partial \omega^n} \right|_{\omega=0} \omega^n \tag{2}$$

The n-th partial derivatives of MTF in spatial frequency $w=0$ is:

$$\left.\frac{\partial^n MTF(\omega)}{\partial \omega^n}\right|_{\omega=0} = \frac{\partial^n}{\partial \omega^n}\left.\int_{-\infty}^{\infty} LSF(x)\exp(-j\omega x)dx\right|_{x=0}$$

$$= (-j)^n \int_{-\infty}^{\infty} x^n LSF(x)dx \quad (3)$$

Hence the n-th statistical moment of function is:

$$m_n = \int_{-\infty}^{\infty} x^n LSF(x)dx = E(x^n) = \int_{-\infty}^{\infty} x^n(t) f_t(t)dt$$

$$= \frac{1}{t_e}\int_{t_x}^{t_x+t_e} x^n(t)dt \quad (4)$$

where t_x is the initial exposure time, t_e is the exposure time; $f_t(t)=1/t_e$ is the PDF of time.

Generally, the expression of MTF is:

$$MTF(\omega) = \sum_{n=0}^{\infty}\frac{m_n}{n!}(-j\omega)^n \quad (5)$$

Based on analysing a large number of vibration information, the vibration is divided into several models: linear vibration, sinusoidal vibration and random vibration. The influence of different vibration modes on the optical imaging system is different, and then we discussed them.

Linear Vibration

Linear vibration leads to image blur for system defocus,

$$x(t) = x_0 + vt \quad (6)$$

where v_0 is the relative speed of the objects to the sensor. The expression of MTF is obtained by substituting Eq. (6) into Eq. (5), setting d (defocusing amount) equal to 0.01, 0.05 and 0.10mm, as shown in Fig.2. The greater the defocusing amount is, the greater the influence of MTF is. In a certain frequency range, the MTF of linear vibration decline rapidly in the low frequency region, and relatively mildly and greatly affects the optical imaging system in the high frequency region.

Sinusoidal Vibration

Sinusoidal vibration also includes high-frequency' and low-frequency sinusoidal vibration', T_0 is the vibration period. For high-frequency vibration, there is one or multiple periodic vibration in a time of exposure t_e, $T_0<t_e$; For low-frequency vibration, $T_0>t_e$, in one vibration period there is one or multiple exposure.

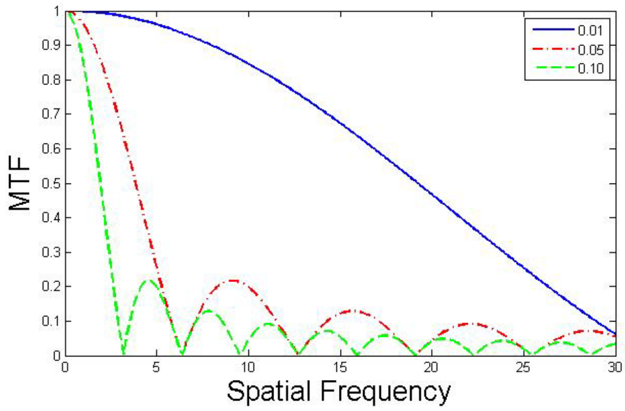
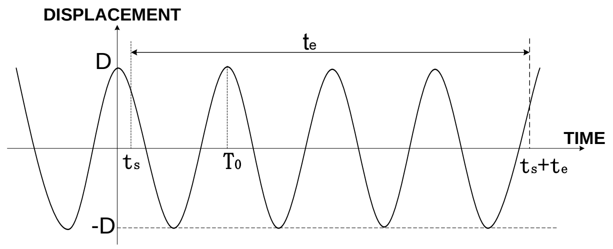
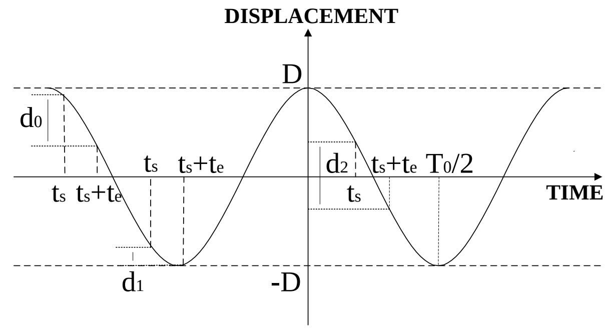


FIG.2. MTF OF LINEAR VIBRATION



(a) High-frequency Vibration $T_0<t_e$



(b) Low-frequency Vibration $T_0>t_e$

Fig.3. SCHEMATIC OF SINE VIBRATION

The high-frequency sinusoidal vibration can be expressed as:

$$x(t) = D\cos(\omega_0 t), \omega_0 = 2\pi/T_0 \quad (7)$$

The MTF of high-frequency sinusoidal vibration is shown in Fig.4. MTF1, MTF2, MTF3 denote MTF tin which D (the amplitude of sinusoidal vibration) is equal to 0.02, 0.05 and 0.10(mm), respectively. Generally, the vibration of the satellite platform causes high-frequency sinusoidal vibration, the influence of the vibration frequency on MTF is relatively minor, the influence of vibration amplitude's is greater, so we must take damping measures to control vibration amplitude in certain scope, and reduce the influence of vibration on MTF to some extent.

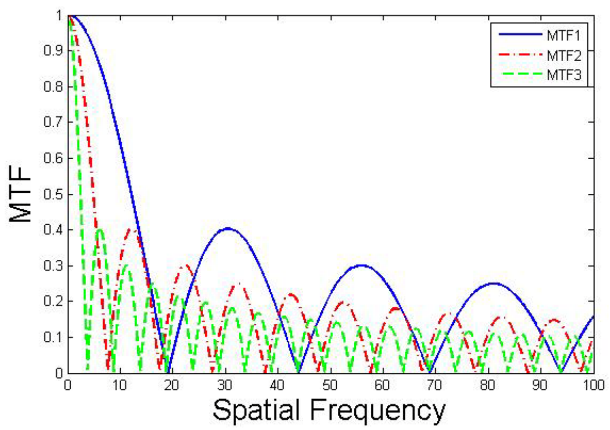


FIG.4. MTF OF HIGH-FREQUENCY SINUSOIDAL VIBRATION

The expression of low-frequency vibration is similar to high-frequency vibration, but the MTF of low-frequency vibration change at the start of exposure. It is a random program. The maximum displacement d_2 is in the period in which the amplitude changes fastest ($\frac{T_0}{4}-\frac{t_e}{2}$, $\frac{T_0}{4}+\frac{t_e}{2}$), image degradation is most serious in this period. When amplitude is less than a certain value, the influence of low frequency vibration can be ignored, reducing amplitude or shortening the exposure time is an effective method to improve MTF.

The MTF Calculation Model of the Two-dimensional Space

For space-borne imaging system, the effect of horizontal vibration and longitudinal vibration on transfer function has been analysed. The vibration of a CCD pixel within exposure time can be seen as a synthesis of the lateral vibration and longitudinal vibration. Image motion caused by the lateral vibration defined as the vibration perpendicular to the optical axis direction. Lateral vibration is the main factor affecting the space-borne camera imaging quality. Longitudinal vibration defined as the direction of vibration along the optical axis direction causes the defocused dispersion spot.

According to the reparability of transfer function, if the quality of the optical imaging system is subject to effect of atmospheric disturbances, mechanical vibration, quality of optical system, the combined MTF can be expressed as:

$$MTF(\omega)=MTF_a \times MTF_v \times MTF_o \times \cdots\cdots \quad (8)$$

where $MTF(\omega)$ is the MTF of the optical imaging system;

MTF_a is the MTF of atmospheric disturbances;

MTF_v is the MTF of the mechanical vibration; and

MTF_o is the MTF of optical system.

Two-dimensional vibration MTF cannot be directly obtained by multiplying one-dimensional transfer function of vibration, because they are not in simple cumulative relationship.

When the motion transfer function is calculated by statistical moment method, LSF of the motion is not needed. It can be simply calculated by using the probability theory and the study of the characteristics of the distribution of order variables, then directly calculated optical transfer function of the system in two-dimensional space. The transverse vibration is denoted as the spatial coordinate x, the longitudinal vibration is denoted as the spatial coordinate y. For the vibration of the two-dimensional space, figure out the MTF on (x, y) within the exposure time, that is the Fourier transform of the point spread function:

$$MTF(\omega_x,\omega_y)=F[PSF(x,y)]$$

$$=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}PSF(x,y)\exp[-2\pi j(\omega_x x,\omega_y y)]dxdy \quad (9)$$

If $PSF(x,y)$ is separable function, it means *PSF(x,y)=PSF(x)×PSF(y)*, the solution for Eq. (9) is the result, expressed as

$$MTF(\omega_x,\omega_y)=\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}PSF(x,y)\exp[-2\pi j(\omega_x x+\omega_y y)]dxdy$$
$$=\int_{-\infty}^{\infty}PSF(x)\exp(-2\pi j\omega_x x)dx\int_{-\infty}^{\infty}PSF(y)\exp(-2\pi j\omega_y y)dy$$
$$=MTF(\omega_x)MTF(\omega_y) \quad (10)$$

This is the simple accumulation multiplication of MTF. However, it is a special case. The vibration mode is very complicated actually. The expression of Point Spread Function (PSF) cannot be described accurately, the expression of MTF still need further derivation. There is the known result, expressed as

$$\left.\begin{aligned}LSF(x)&=\int_{-\infty}^{\infty}PSF(x,y)dy\\ LSF(y)&=\int_{-\infty}^{\infty}PSF(x,y)dx\end{aligned}\right\} \quad (11)$$

Calculate MTF for two-dimension using Taylor

expansion:

$$
\begin{aligned}
MTF(\omega_x,\omega_y) &= MTF(0,0) \\
&+\left(\omega_x\frac{\partial}{\partial\omega_x}+\omega_y\frac{\partial}{\partial\omega_y}\right)MTF(\omega_x,\omega_y)\Big|_{\substack{\omega_x=0\\ \omega_y=0}} \\
&+\frac{1}{2!}\left(\omega_x\frac{\partial}{\partial\omega_x}+\omega_y\frac{\partial}{\partial\omega_y}\right)^2 MTF(\omega_x,\omega_y)\Big|_{\substack{\omega_x=0\\ \omega_y=0}}+\cdots \\
&+\frac{1}{n!}\left(\omega_x\frac{\partial}{\partial\omega_x}+\omega_y\frac{\partial}{\partial\omega_y}\right)^n MTF(\omega_x,\omega_y)\Big|_{\substack{\omega_x=0\\ \omega_y=0}} \\
&+R_n(\omega_x,\omega_y)
\end{aligned}
\tag{12}
$$

By Eq. (11) resulting in

$$
\left.
\begin{aligned}
\frac{\partial MTF(\omega_x,\omega_y)}{\partial\omega_x}\Big|_{\substack{\omega_x=0\\ \omega_y=0}} &= -2\pi j\int_{-\infty}^{\infty} xLSF(x)dx \\
\frac{\partial MTF(\omega_x,\omega_y)}{\partial\omega_y}\Big|_{\substack{\omega_x=0\\ \omega_y=0}} &= -2\pi j\int_{-\infty}^{\infty} yLSF(y)dy \\
\frac{\partial^2 MTF(\omega_x,\omega_y)}{\partial\omega_x{}^2}\Big|_{\substack{\omega_x=0\\ \omega_y=0}} &= (-2\pi j)^2\int_{-\infty}^{\infty} x^2LSF(x)dx \\
\frac{\partial^2 MTF(\omega_x,\omega_y)}{\partial\omega_y{}^2}\Big|_{\substack{\omega_x=0\\ \omega_y=0}} &= (-2\pi j)^2\int_{-\infty}^{\infty} y^2LSF(y)dy \\
\frac{\partial^2 MTF(\omega_x,\omega_y)}{\partial\omega_x\partial\omega_y}\Big|_{\substack{\omega_x=0\\ \omega_y=0}} &= (-2\pi j)^2\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} xyLSF(x,y)dxdy \\
&\vdots
\end{aligned}
\right\}
\tag{13}
$$

The solution for Eq. (13) by statistical moment is

$$
\left.
\begin{aligned}
\int_{-\infty}^{\infty} x^n LSF(x)dx &= E(x^n)=m_n^x \\
\int_{-\infty}^{\infty} y^n LSF(y)dy &= E(y^n)=m_n^y \\
\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} x^j y^k LSF(x,y)dxdy &= E(x^j y^k)=m_{j,k}^{x,y}
\end{aligned}
\right\}
\tag{14}
$$

And the remainder of Taylor expansion

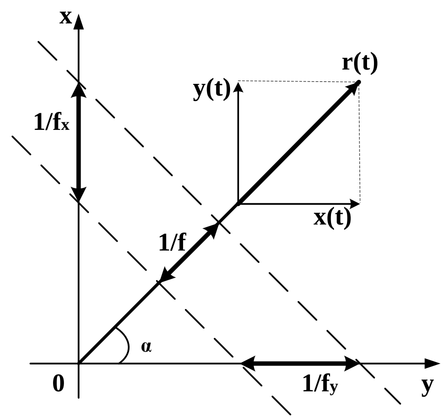
$$
R_n=\frac{1}{(n+1)!}\left(\omega_x\frac{\partial}{\partial\omega_x}+\omega_y\frac{\partial}{\partial\omega_y}\right)^{n+1} MTF(\omega_x,\omega_y)\Big|_{\substack{\omega_x=\theta\omega_x\\ \omega_y=\theta\omega_y}}
$$

$$
(0<\theta<1) \tag{15}
$$

The remainder term can be used to determine the expansion series. At this time, the expression of MTF can be simplified

$$
\begin{aligned}
MTF(\omega_x,\omega_y) &= MTF(0,0)+(-2\pi j)(\omega_x m_1^x+\omega_y m_1^y) \\
&+\frac{1}{2!}(-2\pi j)^2(\omega_x^2 m_2^x+\omega_y^2 m_2^y+2\omega_x\omega_y m_{1,1}^{x,y}) \\
&+\frac{1}{3!}(-2\pi j)^3(\omega_x^3 m_3^x+\omega_y^3 m_3^y+3\omega_x\omega_y^2 m_{1,2}^{x,y}+3\omega_x^2\omega_y m_{2,1}^{x,y}) \\
&+\cdots+R_n
\end{aligned}
\tag{16}
$$

This is the expression of MTF for two-dimension space, in one exposure time (t_x, t_x+t_e), and LSF is equal to the histogram of movement function, the expression is obtained from PDF of time. So the solution for MTF is determined.



FTG.5. TWO-DIMENSION VIBRATION

Conclusions

The Optical transfer function is an important image quality index, The Fourier transform of LSF is the common method in calculating MTF. However, this method is only suitable for one-dimensional case. Statistical moment method uses the probability theory; according to the distribution of variables directly calculate two-dimensional MTF. This paper mainly analyzes the model of the MTF for two-dimensional vibration which is more close to the actual vibration. The method using statistical moment theory is simple to be applied in various forms of vibration.

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